The effect of a strong electric field on the dielectric properties of $LiNbO_3$

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Lithium niobate (LN) $LiNbO_3$ crystals are one of the most popular ferroelectric materials. During the operation of devices based on LN, the stability of their parameters under the influence of external factors is important. Due to the strong pyroelectric properties of LN crystals, its temperature change is accompanied by the appearance of an additional electric field both inside and outside the crystal, which significantly affects the performance properties of the product [1, 2]. Consequently, the question of the possible influence of a strong electric field on the material parameters of LN that are important for the operation of these devices [3] is very fundamental. However, there is no information about direct experiments of studying the effect of a strong electric field on the static dielectric properties of LN crystals, so the state of the problem can only be judged from indirect data that are quite contradictory [4-7]. Therefore, our main goal was to study the influence of a strong quasistatic electric field on the dielectric properties of nominally pure LN.

For experiments, a chip for an optical modulator manufacturing was used. It is a thin (1.00 mm) plate of a non-polar *x*-cut of LN (congruent composition) on the surface of which 5 main electrodes are formed. The width of the chip is 3.45 mm, and the distance from the electrodes to the edges of the chip is 0.80 mm. gaps between the electrodes are 14 μm. Additional electrodes from an indium-gallium eutectic were deposited on the polar faces of the chip. They are designed to control the state of the crystal in the process of making measurements. The investigated chip is shielded and located inside the heating chamber, which allows changing its temperature. The block diagram of the experimental setup is shown in Figure 1.

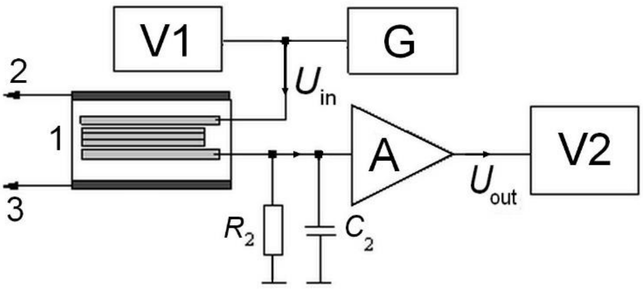

Figure 1. Block diagram of the experimental setup. (1) – chip under investigation; (2) and (3) – additional electrodes on polar surfaces; V1 and V2 – digital ac voltmeters; G – low frequency generator; A – digitally gain programmable ac amplifier.

The chip under investigation can be presented as connected in parallel interelectrode capacitance C_1 and active resistance R_1. Because in our case R_1 >>> R_2, the magnitude of the transmission coefficient of the circuit, containing the investigated chip and the measuring amplifier with K_o gain at angular frequency ω has the following form:

$$|K(\omega)| = \frac{\omega C_1 R_2 K_o}{\sqrt{1+\omega^2 R_2^2 (C_1+C_2)^2}} = \frac{|U_o|}{|U_{in}|},$$

where R_2, C_2 and K_o are known parameters. Measuring of $|K(\omega)|$ allows to calculate C_1.

Direct experiments to study the effect of the electric field on the dielectric properties of LN were performed as follows. Additional electrodes were connected to a device that forms a slowly varying bipolar voltage, so that the maximum value of the potential difference between the chip polar faces was 4 kV. This is equivalent to electric field of E_z = 11.6 kV/cm along the polar axis of the crystal inside a chip of the same size, but without electrodes on a non-polar surface. A further increasing of voltage could lead to electrical breakdown between additional and measuring electrodes despite the fact that the surface of the chip was degreased and dehydrated and a silica gel was present in a chamber. The measurements were carried out at frequencies of 0.1, 1.0 and 10 kHz at a temperature $T \cong 297$ K. Any changes in the capacitance C_1 in the process of increasing the potential difference between the additional electrodes within the accuracy of the experiment was not observed. Changing of polarity of the applied voltage also did not affect the results.

Besides, the detailed study of the dielelectric properties dependence on temperature was carried out for the modulator chip. Figure 2 shows the experimental $C_1(T)$ dependences, which were obtained with and without a short circuit of additional electrodes under the same heating algorithm (maximum heating rate 1.8 K/min). Note, that no marked influence of pyroelectric field E_p on C_1 was observed, while the maximum value of E_p is estimated to be (15 ÷ 22) kV/cm.

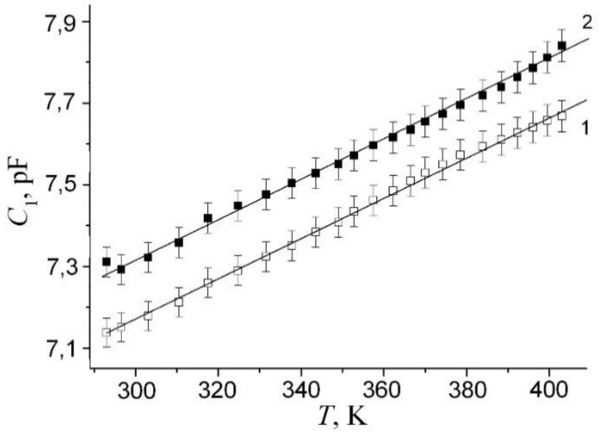

Figure 2. Temperature dependence of the interelectrode capacitance C_1 obtained at a frequency $f = 10$ kHz for: (1) polar faces of the chip are not mutually connected; (2) polar faces of the chip are short circuit.

It can be seen that both dependences do not have obvious anomalies and, within the limits of error, are well approximated by a first-degree polynomial. A slight shift in the dependences relative to each other is caused by the partial restructuring of an alternating electric field in the near-electrode region when additional electrodes are connected to each other. The same experiments were performed at frequencies of 0.1, 1.0, and 100 kHz, and no anomalies were observed similar to experiments at $f = 10$kHz (Fig. 2). Thus, these results represent the first data on the temperature dependence of capacitance (dielectric permittivity) in the complex waveguide-device structure of $LiNbO_3$ modulator chip. Note, that the modulator chip studied is fundamentally different from the bulk-optics $LiNbO_3$ devices. There is inhomogeneity caused by the presence of waveguide within a certain part of the inter-electrode gap. In our chip, the ratio of the width of the gap and channel is 2.4. This inhomogeneity appears when narrow channel waveguides are formed through proton exchange reaction, as the capacitance and resistance within the proton-exchanged areas are different from ones in a rest crystal.

In conclusion, our results indicate that the quasi-static electric fields up to 15 kV/cm directed along or antiparallel to polar axis of LN crystal does not affect its dielectric properties in the low-frequency region within the measurement error.

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